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SELECTING A MINERAL CONCENTRATION PROCESS

By **M.G. FLEMING, B.Sc., Ph.D.**
Professor of Mineral Technology,
Toyal School of Mines

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SELECTING A MINERAL CONCENTRATION PROCESS

by M.G. FLEMING, B.Sc., Ph.D.
Professor of Mineral Technology, Royal School of Mines.

INTRODUCTION

1. Only rarely do mineral deposits exist in sufficient purity to allow them to be mined and supplied directly to the primary consumer. In all but exceptional cases, the ore must first be concentrated to separate the valuable minerals from the worthless rock. Mineral processing, therefore, is an essential part of the development of natural mineral resources; whether in the production of suitable raw materials for home industries like fertilizers, cement and glass manufacture or in the preparation of marketable products for export such as metallic mineral concentrates. Mineral technology has expanded rapidly to meet increasing demands for mineral products and a wide variety of treatment methods is available.

2. However, there is no simple formula for selecting a concentration process. The size, grade and mineralogical composition of the ore body; technical considerations of mining and mineral processing; accessibility; markets and the availability of capital are inter-related factors which must all be considered before a decision is reached. The selection is further complicated by the fact that more than one technical solution is usually possible and estimation of the economic factors involves long-term predictions with a wide margin for error.

3. This paper attempts a broad outline of the limitations and potentialities of modern mineral processing techniques. It is hoped that it will assist government officials responsible for development of their countries' mineral resources to view the various aspects of these problems in perspective.

TECHNICAL CONSIDERATIONS

4. The earth's crust is composed of some 3,500 mineral species, each identifiable by its basic crystal structure and other physical and chemical properties. Only 300-400 are common or important constituents of ore deposits and a typical ore may contain 10-20 of these. The proportion of valuable mineral present determines the grade or richness of the ore, but the kind and proportion of the other mineral components - the gangue - are equally important in determining the mode of separation that may be employed. The possible combinations are, thus, enormous and, while they may have similarities, no two ores are identical. Furthermore, the geological origins or genesis of mineral deposits result in variation in composition and the relative proportions of mineral constituents within a single ore body. This infinite variety makes every mineral processing problem unique and distinguishes the concentration of ores from other industrial operations.

5. Since most ores are mined or quarried from solid rock with their mineral constituents firmly locked together, the first step in any concentration process is to liberate the valuable mineral grains from the matrix or gangue with which they occur. This is done by crushing or grinding in stages until the entire mass of the ore is so fine that the valuable mineral exists essentially as separate and discrete grains, uncontaminated by adhering gangue. With rich, coarsely-crystalline ores an effective degree of liberation may be achieved at lump sizes. With fine-grained, intimately intergrown ores this may involve grinding to a maximum particle size of less than 0.05 millimetres, or about two-thousandths of an inch. Even when the ore deposit is a soil or sand or loosely-compacted rock, some form of grinding is usually required to break up aggregates and to remove coatings from the mineral surfaces which would otherwise complicate the subsequent concentration process by masking their specific properties.

6. All mineral processing is based on the exploitation of differences in the properties of the mineral constituents. For example, a typical tin-tungsten ore may contain cassiterite (tin oxide), wolframite (iron-manganese tungstate), quartz and half a dozen other silicates. The gangue minerals are relatively light and the property of specific gravity may be exploited to remove them from cassiterite and wolframite. However, the distinction between the two valuable minerals with regard to this property is insufficient to permit them to be separated by gravity methods and some other treatment is required. Usually, wolframite is magnetic and cassiterite is not; so that magnetic separation may be employed for the final stage. Occasionally, however, the cassiterite associated with a particular ore deposit contains minute quantities of iron and its magnetic susceptibility overlaps that of wolframite; in such cases another method, based on a different property, must be sought. This inconstancy in a mineral species is a further complication familiar to mineral processing engineers.

7. In addition to specific gravity and magnetic susceptibility, physical properties forming the basis of mineral separation techniques include: colour, lustre, hardness, shape, electrical conductivity, fluorescence and radio-activity. The chemical properties of minerals are even more diverse than their physical properties and leaching with selective solvents, which will dissolve the valuable minerals while leaving the gangue minerals unaffected, is a method of chemical processing commonly used for the recovery of gold and uranium and, increasingly, for the recovery of other metals from complex ores. Gas-solid reactions at moderately high temperatures provide another form of chemical treatment frequently used as a stage in mineral processing operations. The physico-chemical properties of mineral surfaces provide the basis for the most important of all concentration techniques - the froth flotation process.

8. Figures I and II illustrate some of the methods used commercially to separate minerals according to their different properties. With simple ores, a single technique will often provide a suitable concentration. With complex ores, these and other techniques must be linked together to separate first one group of constituents and then another until the impurities are finally eliminated and only the valuable minerals remain.

9. All of these methods have their limitations. The properties of minerals which occur together in a particular type of ore deposit frequently overlap. Impurities, like the trace of iron contained in some types of cassiterite which was mentioned earlier, often interfere with a process. Chemical methods usually require the addition of at least equivalent quantities of reagents or of fuel to supply heat and their cost may exceed the value of the product. However, the most common limitation is that imposed by the size and the mass of the particles after they have been liberated. Figure III shows the size range over which a

number of well-known mineral processes are effective. In each case the efficiency falls off towards the lower end of the size scale and many of these methods are either useless or will yield low recoveries when applied to ores which require fine grinding for the liberation of their constituent minerals. On the other hand, insufficient grinding provides incomplete liberation and this, in turn, results in low-grade concentrates and poor recovery of values. Unliberated particles or middlings, consisting partly of valuable mineral and partly of gangue, have properties lying between the two and no concentration process can treat them effectively.

GEOGRAPHICAL AND ECONOMIC CONSIDERATIONS

10. In addition to the basic mineralogical and process limitations are limitations imposed by geographical and economic considerations. These include the cost and availability of water, fuel, power, reagents and other supplies, suitable labour, facilities for the disposal of waste materials, transportation and the existence of a steady and profitable market for the product. The possible influence of each of these factors is important and so varied as to be quite beyond the scope of this paper. However, a few examples may serve to illustrate their influence on the selection of a concentration process.

11. Water. In most mineral dressing operations the ore is ground in water and concentration is effected in a water suspension. The quantity required may be as much as nine tons of water for each ton of ore treated, although an appreciable proportion of this may be re-used if the circumstances warrant the additional cost of reclamation. Not only the quantity but the quality of the available water may be a decisive factor in choosing a process. Hard waters, for example, are unsuitable for use with soap or fatty acid reagents while amines, another type of collector frequently employed in flotation, are precipitated by dissolved or colloidal silica from natural waters.

12. Fuel. Dry processes, on the other hand, require the feed to be bone dry and, even in very arid regions, this may necessitate artificial drying during at least part of the year. To prepare an ore containing, say, 5% moisture for high tension electrical separation would necessitate the supply of about a gallon of fuel oil per ton to reduce it to the essential limit of 0.5% moisture.

13. Power. Crushing and grinding account for the greatest proportion of power consumed in ore treatment. The requirement may range from as little as 5 kWh/ton of ore for the concentration of a beach sand to 50 kWh/ton for the flotation concentration of a hard rock ore which is liberated only at very fine size. The cost of power is equally variable - about 0.025 sh. per kWh from a convenient hydroelectric grid in Norway but as much as 0.3 sh. per kWh from a diesel generator in Bolivia. The examples chosen thus show an extreme range of 0.1 to 15 sh. per ton of ore treated for power costs alone.

14. Reagents and other supplies. The cost of all supplies is necessarily high in inaccessible areas. Grinding balls which cost £60/ton in the U.S.A. cost £80 by the time they have been delivered to a remote plant in Peru. With sulphuric acid at £5/ton in Northern Rhodesia an acid leach process is attractive which could not be contemplated in southern Tanganyika, where the cost is £50/ton.

15. Labour. Steady, efficient production requires skilled, conscientious and experienced operators. Except on small, "shoestring" operations, however,

the lack of an industrially experienced local labour force is seldom a process limitation, for the deficiency can always be made good by intelligent training and close supervision.

16. Disposal of Waste Materials. In remote regions, the disposal of mill effluents presents no problems but, in populated, agricultural areas of central Africa or India, the control of waste and the avoidance of stream or river pollution is an important aspect of process design.

17. Transportation. The increase in cost of reagents and supplies caused by high freight charges and the consequent effect on the economics of many processes have already been mentioned. The cost of transporting mineral products to a ready market may be equally critical in determining the kind of process or the degree of concentration necessary to make an operation profitable. For instance, the mineral fluorspar is commonly marketed in two main grades - "metallurgical spar" with a specification of 87% CaF_2 and "acid spar" with a specification of 96% CaF_2 . The first sells at about £14/ton in Europe and the second at about £19/ton. The difference in these prices might easily mean the difference between a profit and a loss if the product had to bear appreciable freight charges and might well justify the additional capital cost and higher operating costs that would be required by a plant capable of producing premium grade spar.

18. Markets and Product Specifications. Second in importance only to the limitations imposed by the mineralogical nature of the ore are those imposed by buyer and consumer. All mineral products are sold to specifications which control not only the valuable mineral content but, usually, the size distribution and the proportions of certain deleterious impurities. The process must be designed to meet these specifications. Metal prices are subject to the same kind of fluctuations as agricultural products. For example, in the last twelve years the price of copper has ranged from a high of £436/ton to a low of £160/ton, lead from £180 to £ 57 and tin from £1,615 to £ 570. Non-metallics are sold, for the most part, by private contract to the buyer's specifications. It is obvious, therefore, that selection of the most suitable mineral process depends to a large extent upon marketing considerations.

ORE TESTING

19. Technical problems associated with the selection of a process are resolved by laboratory testing of representative samples of the ore. This comprises three stages: the first to determine the nature of the ore and its amenability to the various concentration techniques, the second to develop a detailed process and the third to provide engineering data for the design of the plant.

Amenability Testing

20. The first stage is diagnostic. It classifies the problem and assesses the difficulties to be overcome in its solution. It is qualitative rather than quantitative. The general mineralogy of the ore must be established and related to the methods of concentration available. Not only must the mineral constituents be identified but their crystal interlock and size characteristics must be determined. Macro- and microscopical examinations are supplemented by heavy liquid and superpanner tests on ground and sized products. Chemical tests and specialized techniques fill out the information necessary to state the problem in mineral dressing terms and to enable the most promising process or combination of processes for concentration of the valuable constituents to be tentatively selected. From his own experience and the published

experience of others, the investigator will decide on the initial conditions for batch testing of the ore by the selected process and, from this starting point, he will embark on a series of tests in which every condition and every product is closely examined at each stage of the operation. Scientific reasoning combines with experience and judgement to interpret the observations and to modify the conditions from one test to the next.

21. In general, the results of the amenability tests will place the problem in one of three categories:

- I A simple straightforward ore responding to conventional methods of treatment with results similar to those obtained in well-known commercial operations and revealing no unusual or complicating features;
- II An essentially simple ore which has responded reasonably well to treatment but which has exhibited some unusual characteristics that might complicate a normal operation if they proved to be persistent;
- or a complex ore of a familiar type which is known to be difficult to treat and the behaviour of which can only be predicted by the detailed examination of samples representing every portion of the ore body;
- III Ores for the treatment of which no established precedent exists. Unusual minerals or mineral associations which have not previously been successfully concentrated. Complex crystal intergrowths or grain coatings which make it exceptionally difficult to achieve liberation of the ore into discrete mineral particles. Partially decomposed ores and soils in which the valuable constituent may be present in a wide range of secondary minerals in varying stages of alteration.

22. Most ores will fall into the first category, but an appreciable proportion of ores belong to the second category. With these, amenability tests provide warning that an exploratory ore testing phase will be necessary before detailed testing for the development of a concentration process can begin. Such problems are often recalcitrant and the time and effort needed for their solution is not safely predictable. Ores of the third category represent a research problem that may occupy a team of experts for five years or more although, as the way is uncharted, there is no certainty of a successful solution in terms of current economics.

Process Testing

23. In this stage is included all the work necessary to solve the basic metallurgical problem revealed by amenability testing and subsequent exploratory work. With simple ores of the first category the inference with regard to treatment method is reasonably clear, but optimum conditions must be determined for each stage of the process and carefully related to the geographical and economic aspects of the problem.

24. With ores of the second category an additional exploratory phase is necessary and, even when this has been successfully completed, the development of a treatment method may be a long and tedious business. The processing

of complex ores frequently involves the resolution of a very large number of simultaneous variables and the amount of laboratory work required may be formidable. The final decision as to what constitute the optimum conditions requires the careful assessment of test data from which grades, recoveries and costs can be weighed and compromised, and must usually be confirmed by continuous operation in a pilot plant.

25. For ores of the third category, all of these factors are accentuated by the unusually complicated nature of the problem.

Detailed Design Testing

26. Following the selection of a concentration process, a final stage of ore testing is necessary to provide full data on flow rates, volumetric capacities, circulating loads and other circuit details required for the engineering design of the plant. This work can only be commenced when the process has been fully agreed and must be carried out in close collaboration with the engineers responsible for the design and erection of the plant.

Cost of Ore Testing

27. It is quite obvious that no fixed scale of charges is possible for ore testing because the cost will vary widely according to the nature of the ore and the extent to which the investigation is pursued. Many machinery and reagent manufacturing firms maintain laboratories which undertake limited investigations free of charge or at nominal cost in the prospect of subsequent sales. Private and government research establishments usually estimate the cost of amenability tests on the basis of past experience with similar problems and, when the amenability tests have been carried out, work to an agreed budget. The following estimates, which do not include allowance for continuous pilot plant testing, may be useful as a rough guide:

Example A: A simple tin ore containing some sulphide minerals.
Category I.

Estimate for amenability testing	...	...	...	...	£150
Allowance to be made for process testing	...	...	...	...	£350

Example B: A fairly complicated copper ore containing large quantities of pyrite and small quantities of lead and zinc sulphides. Category II.

Estimate for amenability testing	...	...	...	...	£200
Allowance to be made for process testing	...	...	...	...	£800

Example C: A rather complex fluorspar ore from which it is hoped to produce acid grade spar by flotation.
Category II.

Estimate for amenability testing	...	...	...	...	£250
Allowance to be made for process testing	...	...	...	...	£1,250

Ore Testing in Less Developed Countries

28. In the past thirty years the empirical art of ore dressing has become a complex technology and "trial-and-error" methods of testing have given way to the systematic organization of industrial research. A fully equipped, modern laboratory represents a very large investment that could only be justified and supported in a country with an important and flourishing mining industry. These facilities already exist in many countries and, through technical aid schemes, the impartial assistance of such establishments as the Warren Spring Laboratory of the Department of Scientific and Industrial Research may be obtained for any complex or difficult mineral processing problem.

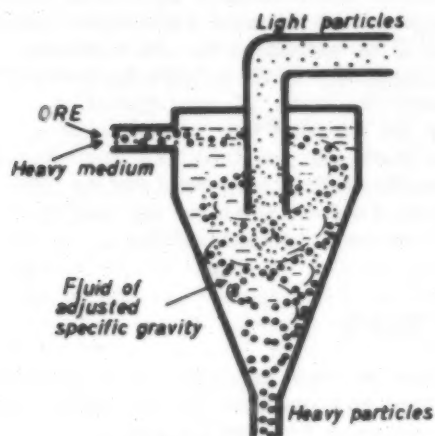
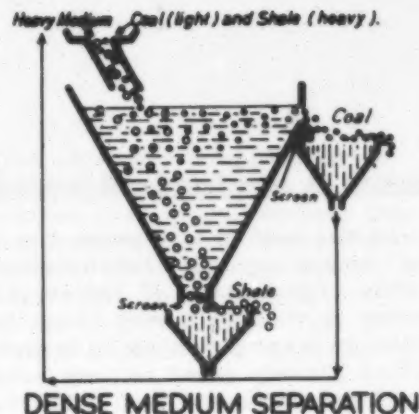
29. This is not to suggest, however, that less industrialised countries should not have their own ore testing laboratories. In the author's opinion, such facilities are an integral part of the development of mineral resources anywhere and should grow with the industry they serve. In addition to the obvious advantages of carrying out preliminary investigations with a full appreciation of local conditions, these laboratories complement the work of geological surveys, disseminate technical information and do much to improve the practice of small mineral processing operations. Much useful work can be done and much experience can be gained in a modestly-equipped, inexpensive laboratory as long as its essential limitations are appreciated and it is free to call on the highly specialized services of a large, experienced research establishment.

CO-ORDINATION AND TIMING

30. Amenable testing should be undertaken as soon as sufficient geological evidence has been obtained to justify a detailed exploration of the discovery and as soon as the deposit has been sufficiently exposed to provide samples indicative of its general mineralization. The stage described as process testing would not ordinarily be justified until it was clear that the ore body was of sufficient size and value to make its exploitation economically attractive. Furthermore, unless there was material available that was similar in grade, mineral distribution and grain size to that which the plant, when built, would have to treat, much of the work would have to be repeated when the true character of the ore body became apparent. The importance of having samples for testing which are representative of the ore which will have to be treated cannot be over-emphasized. The point is so elementary as to seem inescapable and yet, time and again, expensive and painstaking investigations are carried out on samples which prove to be quite different in certain essential characteristics from the material which will make up the plant feed.

31. Mining exploration to establish the ore reserves, process testing, market surveys and the assessment of power, water and other supplies are all essential factors in the development of a mineral deposit. Their interdependence necessitates the closest co-ordination at every stage. The selected concentration process must be suitable for the particular ore body which it is designed to treat, it must operate efficiently under the restrictions imposed by its location and its products must be marketable at a profit.

Most metallic minerals have a higher specific gravity than the gangue minerals with which they are associated. For ores that liberate at coarse sizes, this simple method works well and millions of tons of metallics, non-metallics and coal are treated daily by the dense medium separation process. The vessel is filled with a heavy liquid or, more frequently, a suspension of finely ground heavy solids which acts as a fluid medium of adjustable density. "Floats" flow over the top while "sinks" are drawn out the bottom of the vessel. The products are screened to separate them from the medium which is recycled.



Small particles would settle too slowly in a bath of the type shown above, so centrifugal force is used to augment the force of gravity and speed up the separation. Feed consists of a mixture of fine ore and heavy medium and is pumped under pressure into the conical vessel. The low specific gravity minerals flow out of the top while the heavy minerals are removed from the bottom. As before, the products must be screened to separate them from the medium. Large forces can be developed and cyclones have amazing capacity for their size. Hydrocyclones, using only water as the medium, are employed to classify material into different size fractions and to remove fine slimes.

Magnetic permeability is a property that is shared in some degree by all minerals containing iron. For strongly magnetic minerals like magnetite, methods of the kind illustrated here are effective. For weakly magnetic minerals like hematite, wolframite or columbite, much more intense magnetic fields must be employed. As with most mineral processes, the products are frequently retreated in similar machines to clean the concentrates and to remove the last trace of magnetics from the tailings.

MAGNETIC SEPARATION

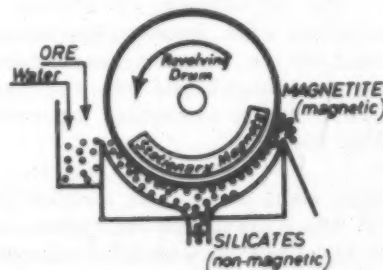
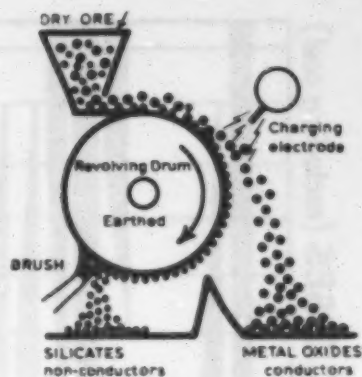


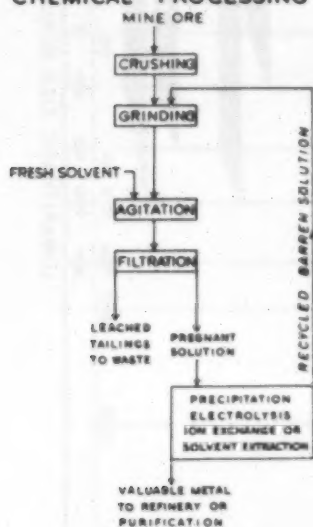
Figure I

Electrical methods of separation depend on the fact that the conductivity of minerals varies widely. Using charges of up to 50,000 volts, conductors like ilmenite or rutile may be separated from insulators like quartz or zircon. Dry ore is fed on to an earthed revolving drum. The ore particles are indiscriminately charged by the electrode but the conducting minerals quickly lose their charge to the earthed drum and are thrown off in a normal trajectory. The insulators are attracted to the drum and are removed as shown.



HIGH TENSION SEPARATION

CHEMICAL PROCESSING



The diagram shows a generalized flowsheet for the chemical treatment of an ore by leaching. The process depends on the existence of a cheap, selective solvent and is used to recover gold, silver, uranium, copper and other metals from complex ores. A gold ore would be crushed and ground to expose the minute particles of precious metal and then agitated for 24 hours in a pulp or slurry with a dilute solution of sodium cyanide. This selectively dissolves the gold and the pregnant solution is then filtered off, precipitated with zinc dust and the zinc-gold precipitate is melted and refined to produce bullion.

Flotation exploits differences in the surface-chemical properties of minerals. A myriad of air bubbles is blown through a water suspension of finely ground ore in which the desired minerals have been selectively waterproofed by the addition of suitable chemical reagents. The valuable particles attach to the bubbles, rise to the surface and are skimmed off as a froth, leaving the wetted gangue particles in the suspension. The development of this sensitive process has opened up thousands of ore deposits that were too low grade or too complex to be treated by other methods.

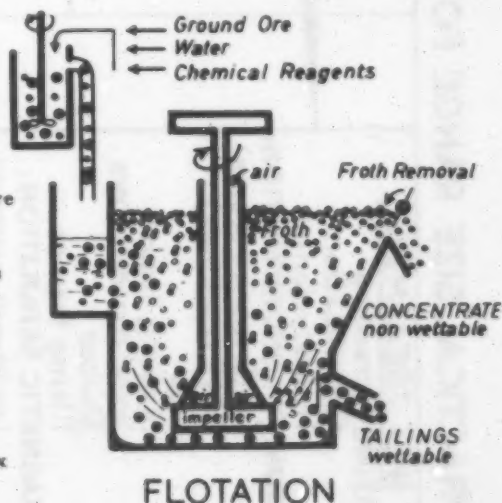


Figure II

PRACTICAL SIZE RANGE FOR VARIOUS MINERAL UNIT PROCESSES (excluding coal)

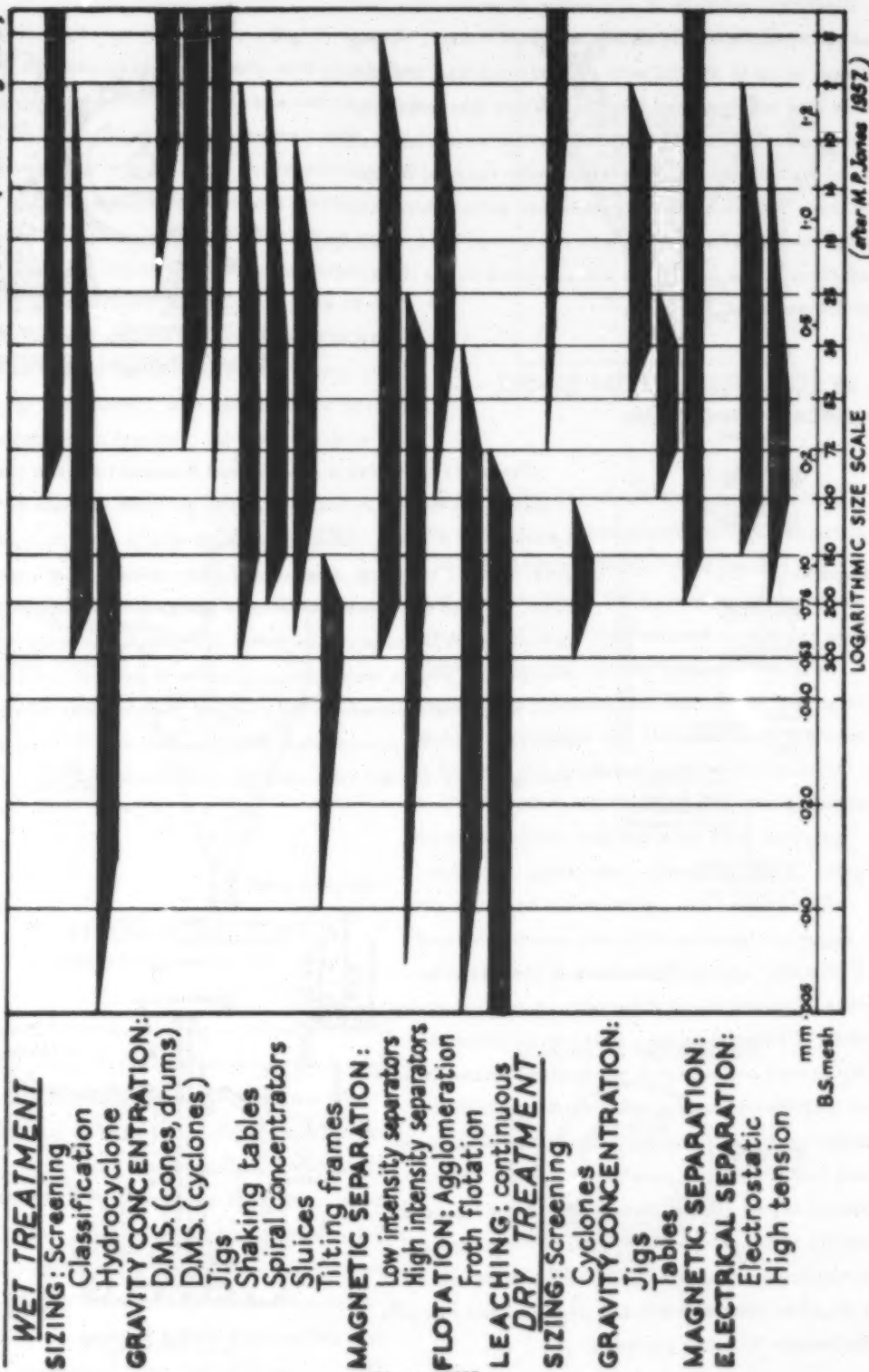


Figure III